EA-RYGNC-HB-001-1-0

Project

EAGLE

Handbook

User Manual

Revision 5794

March 05, 2019

Editor

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DLR HB RY-GNC

Deutsches Zentrum
für Luft- und Raumfahrt
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Acronyms

CoM Center of Mass.
CSV Comma Separated Values.

DLR Deutsches Zentrum für Luft- und Raumfahrt.

EAGLE Environment for Autonomous GNC Landing Experiments.
ECU Electronic Control Unit.
EGSE Electronic Ground Support Equipment.
EGT Exhaust Gas Temperature.
ET-NAV EAGLE Tag Navigator.

FoV Field of View.

GNC Guidance, Navigation, and Control.
GPS Global Positioning System.
GS Ground Station.
GUI Graphical User Interface.

HiL Hardware-in-the-Loop.

ICD Interface Control Document.
IMU Inertial Measurement Unit.

KF Kalman filter.

LiPo Lithium-ion Polymer.

MCI Mass, Center of Mass, Inertia.
MEMS Microelectromechanical Systems.

NEST NEST Environment for Suspended flight Tests.

OBC On-board computer.

PFD Primary Flight Display.
PPE Personal Protective Equipment.
PWM Pulse Width Modulation.

RTK Real Time Kinematic.

SiL Software-in-the-Loop.

TAT Turnaround Time.
TM/TC Telemetry/Telecommand.
TVC Thrust Vector Control.

VTOL Vertical Take-Off and Landing.

w.r.t. with respect to.

Frames and Reference Points

ACC Accelerometer.
BARO Barometer.
B Body.
ECEF Earth Centered, Earth Fixed.
ECI Earth Centered Inertial.
ETNAV Camera of ET-NAV.
TAG Tag map frame of ET-NAV.
GPS GPS (Antenna).
GSR Ground Station Reference system.
GYR Gyroscope.
I Inertial.
LA Laser Altimeter.
MAG Magnetometer.
M Mechanical.
NAV Navigation.
NED North East Down.
TVC TVC frame along vane axes.
WGS World Geodetic System.

Notation

A Matrix valued variable (upper case).
A^T Transposed of A.
$E\langle\rangle$ Expected value.
$\hat{a}$ Estimated value.
$\mathbf{a}$ Vector valued variable (lower case, bold type).
$\mathbf{q}_A^B$ Attitude transformation quaternion from frame A to frame B.
$\mathbf{r}^A$ Position of the origin of NAV frame in frame A.
$\mathbf{r}_B^A$ Position of the origin of frame B in frame A, if B is omitted NAV is to be assumed.
$\mathbf{r}_P^A$ Position of the point P in frame A.
$\mathbf{r}^B = T_A^B \cdot \mathbf{r}^A$ transforming position from frame A to B.
$\mathrm{diag}()$ Diagonalization of a vector.
$\otimes$ Quaternion multiplication ($\mathbf{q}_A^B = \mathbf{q}_C^B \otimes \mathbf{q}_A^C$).
$[\mathbf{a}]_\times$ Skew symmetric form of a vector.
$\tilde{a}$ Measured value.
$\times$ Cross product.
a Scalar valued variable (lower case).

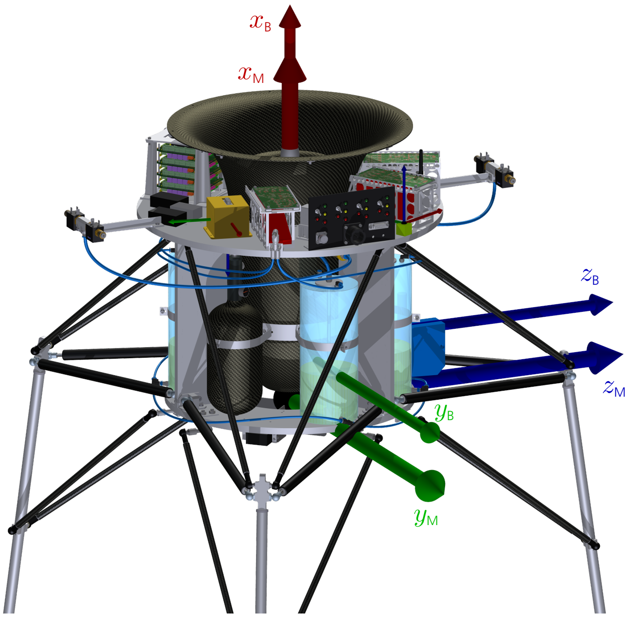


Figure 1: Mechanical and Body System Defined for EAGLE

1 Introduction

This document is an overview of the Environment for Autonomous GNC Landing Experiments (EAGLE). This manual gives a basic insight into the design of this platform and its justification. The general design of EAGLE is described in Section 3. The section concerning the flight envelope (4) provides an impression for what kind of studies EAGLE can be utilized and what performance can be expected. The key limits and performance indicators are justified within Section 5.

Section 6 describes the basics about the Guidance, Navigation, and Control subsystems and how a user of EAGLE can expect a modification/adaption procedure to work. The focus for adapting EAGLE is verifying new software algorithms but also small payloads can be tested. A further detailed look into the possibilities and procedures for adapting EAGLE is given in Section 8.

Figure 1 shows the mechanical (M) and the body (B) reference frame of EAGLE. Because EAGLE resembles a Vertical Take-Off and Landing (VTOL) vehicle the roll axis points upwards.

If one assumes hovering as the standard case for EAGLE, then it is reasonable to think about a front/back, and left/right. The z^M axis points forward, and the y^M shows to the right of EAGLE. The angle definitions are kept for consistency reasons around the appropriate axis:

- Around x^B: roll angle ϕ
- Around y^B: pitch angle θ
- Around z^B: yaw angle ψ

The body system (B) is placed at the Center of Mass (CoM) with the same orientation of the mechanical system (M). The translation between both theses system depends on the mass distribution of EAGLE, which changes with the fuel level or by installing payloads.

The navigation state can be expected in either frame and the alignment of the avionics and mechanics is given in Section 9. The Section 9 lists the known parameters of EAGLE, e. g. the Mass, Center of Mass, Inertia (MCI) of the base configuration.

2 Roadmap

The following table shows the anticipated roadmap for the development stages of EAGLE.

Table 2: Envelop Expansion Roadmap

Milestone	Year	Quarter	Test site	Accomplished	Description
Tethered Flight	2017	2	DLR Bremen	✓[1]	EAGLE stabilizes attitude, altitude, and position within the tethered flight facility.
Controller tuning and verification	2017	3-4	DLR Bremen	✓[3]	Improve the controller quality and test its limits, e. g. introduce delay to actuator signal, and put de-balance mass on EAGLE.
Guidance	2018	1-2	DLR Bremen	✓[3]	A working guidance scheme was proven within the tethered flight facility.
Lift-Off and Landing	2018	2	DLR Bremen	✓[2,3]	EAGLE can lift-off and land from the launch pad.
Free Flight Permission	TBD				Required permission for flying EAGLE within a restricted airspace was granted.

These major milestones can have an influence on the flight envelopes in Table 3 and 5.

1 https://gnc.dlr.de/s/yt/eagle-tethered-flight
2 https://gnc.dlr.de/s/yt/eagle-liftoff-landing
3 https://gnc.dlr.de/s/yt/eagle

Figure 2: Environment for Autonomous GNC Landing Experiments

3 Environment for Autonomous GNC Landing Experiments

EAGLE is a VTOL vehicle for testing vertical launches and landings. The most apparent attributes seen in Figure 2 are the landing legs and the main structure centrally housing the main engine. The main engine is a one stage jet engine capable of lifting the roughly 30 kg wet-mass of the lander. The landing gear absorbs the landing shocks protecting the sensitive electronics, payloads, and the structure itself.

3.1 General Configuration and Layout

The light-weight main structure of EAGLE is built from five *aluminum sandwich* parts interconnected with aluminum brackets and clamps. Figure 3 shows the two rings that are linked with three (identical) vertical belts. The upper ring is the *electronics bay* housing the overall avionics of the lander, the *base plate* anchors the landing gear adapters and closes the middle section for the fuel and gas tanks.

The central cutaway is reserved for the main engine and the Thrust Vector Control (TVC) system inside the exhaust stream of the turbine.

Figure 4 shows the functioning of the landing gear system. Each leg is connected with four carbon rods supported with joints on each side. Additionally, two gas dampers for each leg hold the legs in the extended position (Figure 4a) or give in during landing (Figure 4b). A single leg was tested on a test bench with a dummy mass of 15 kg. It survived multiple falls from a height of 1.5 m without damage.

3.2 Actuation

Three actuation systems are integrated on the lander. First of all, the jet engine (Section 3.2.1) generating the main thrust by commanding the fuel flow into the jet engine's burning chamber. Second, a TVC system (Section 3.2.2)

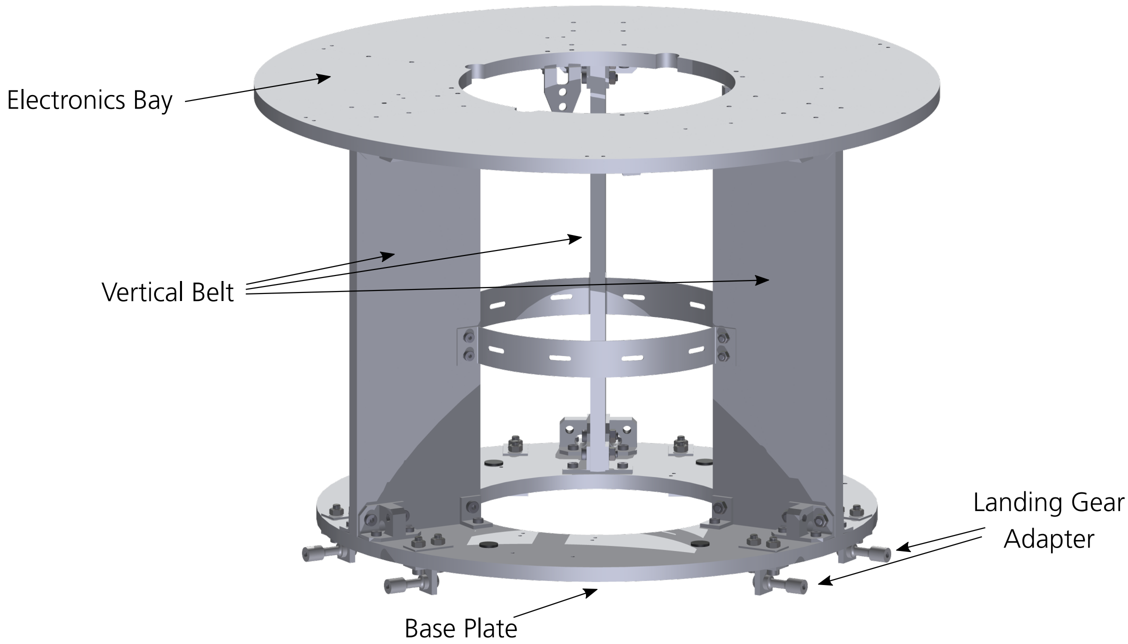


Figure 3: Main Sandwich Structure of EAGLE

(a) Extended (Nominal) Landing Gear Position

(b) Retracted Landing Gear Position

Figure 4: Landing Gear System of EAGLE

employing two vanes aligned perpendicular to each other to deflect the thrust for *pitch* and *yaw* maneuvers (like a rocket or launch vehicle the *roll* axis points upwards in the main flight direction). And last, the roll actuation system (Section 3.2.3) implemented as a cold gas thruster system.

3.2.1 Jet Engine and Fueling System

The jet engine generates the main thrust to act against the gravitational forces and accelerate the vehicle. Its maximal nominal static thrust is around 400 N at sea level at which the one-stage-radial compressor (and the one-stage turbine) rotates with approximately 100 000 RPM. The only command necessary to control the engine is the *pump voltage*. It is issued to the Electronic Control Unit (ECU) which provides the commanded voltage to the fuel pump. Additionally to

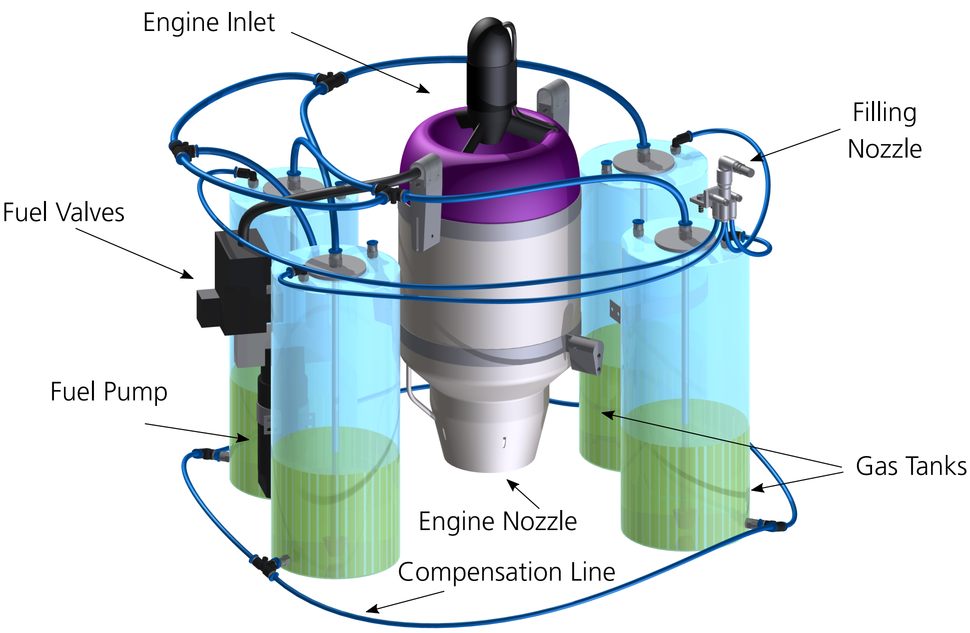


Figure 5: Main Engine and Fueling System

the command, the communication with the ECU includes housekeeping data for monitoring the complex jet engine system.

The whole engine and fueling system is depicted in Figure 5. In the center of the setup the compact engine is shown with the inlet on the upper side and the exhaust nozzle on the lower side. It is surrounded by four 1.8 l kerosene tanks that are all interconnected with regard to the filling, suction, and compensation. The compensation line equalizes the fill level of all tanks after the system was fueled. The diameter of these hoses are chosen to be small to minimize the effect of shifting fuel mass during tilted flight.

The fuel system includes two control and safety valves which are placed right after the fuel pump in the system. One is used during the start-up procedure of the engine and the other is used to prevent any fuel entering the burning chamber when it is not necessary.

3.2.2 Thrust Vector Control System

For controlling the attitude around EAGLE's pitch and yaw axis a TVC system is placed on the lower side of the main structure. Figure 6 shows the main components that constitute the system. Each control motor rotates a shaft that is connected to a vane. The controllable deflection angle for each vane is about $\pm 12°$. Higher angles are not possible due to the "v"-shaped cutouts of the vanes where the perpendicular axes cross. Each vane is supported by two ceramic ball bearings which can handle the high temperature of the exhaust stream of the engine better than steel bearings.

It is important to notice that the control authority of a motor is not aligned with a body axis. The front leg is mounted on the right side in Figure 6, showing that both vanes must be used to result in a pure pitch maneuver, or pure yaw maneuver.

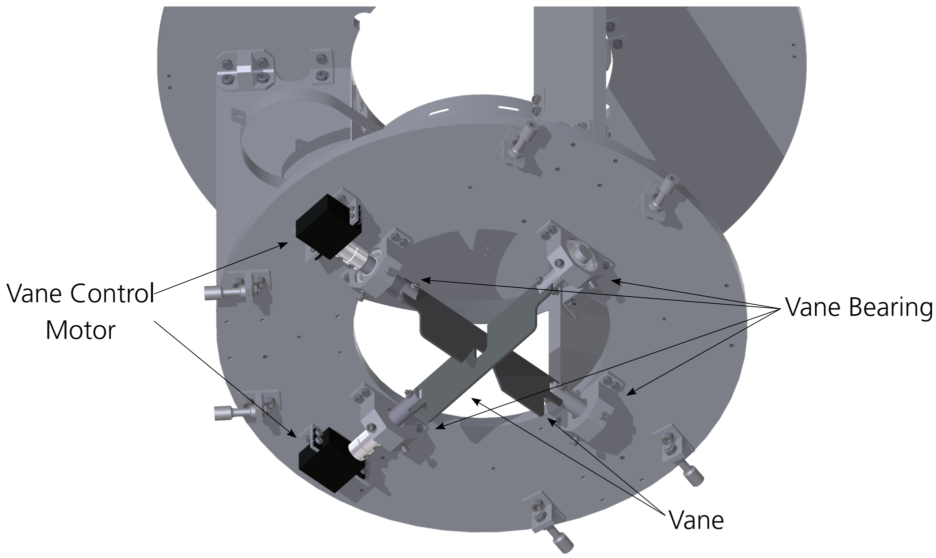


Figure 6: Thrust Vector Control System

The effectiveness of the system is highly depending on the main thrust. Tests with a thrust of about 220 N showed forces perpendicular to the main thrust at maximal deflection angle of about ±35 N.

3.2.3 Roll Control System

Figure 7 depicts the roll control system mounted on the EAGLE structure. The actuators that generate the control forces are connected to the front and back lever arm and consist of electronic on/off valves and a nozzles. The valves are fed with pressurized air over a hose connected to the *low pressure regulators*. The *low pressure regulators* are in turn connected to the *high pressure regulators* screwed directly into the pressure tanks.

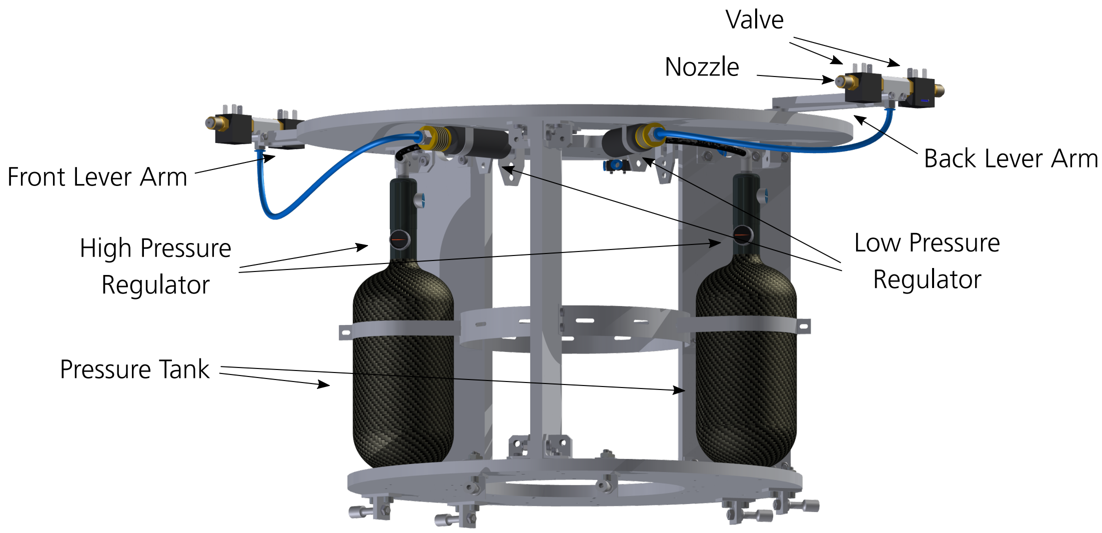


Figure 7: Cold Gas Based Roll Control System

The tanks hold 300 bar at 1.1 l when full which is reduced over the two-staged system to 12.5 bar at the valves. The nozzle is screwed into the outlet of the valve with a design optimized for a nominal control thrust of 4 N.

The design of a cone nozzle with a small slope of 5° was chosen for simple manufacturing, still resulting in a reasonable efficiency. The pressure in front of the valves is regulated to achieve this nominal thrust of 4 N with a lever arm of 405 mm, resulting in the maximal control torque of about 3.24 N m, if both nozzles per directions are commanded.

3.3 Avionics and Software Design

Figure 8 shows a schematic of the avionics on board of EAGLE. The main element is the On-board computer (OBC) which has (indirect) access to all available sensors and actuators. Depending on the electrical interface of a device it is either connected directly to the OBC, or the data stream is routed via an *Interface Board* that provides access to low-level interfaces (SPI, I^2C, PWM, etc.).

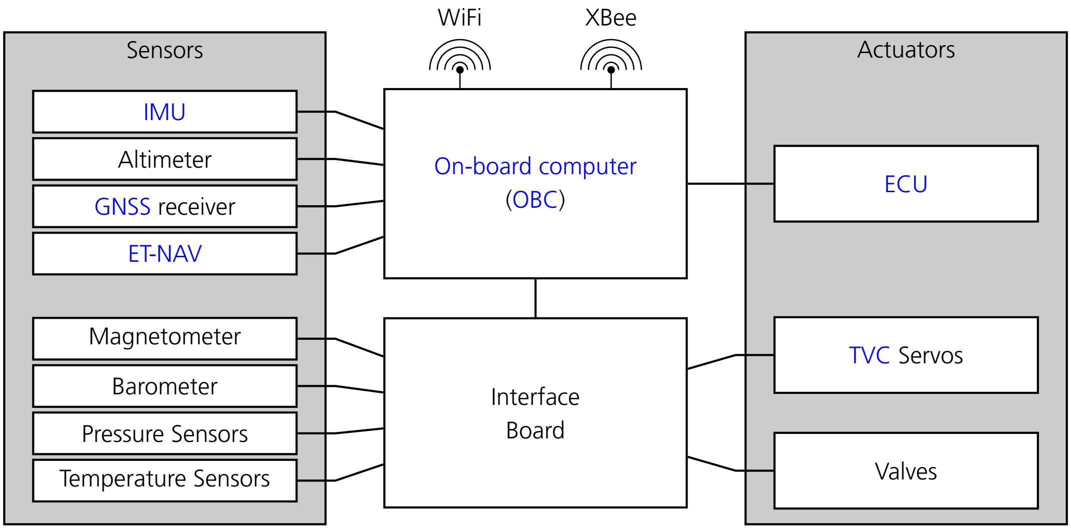


Figure 8: Avionics Overview of EAGLE

Communication with the ground station is guaranteed via two different wireless links on two different frequency bands (WiFi and XBee). In case of a disrupted WiFi link, the low bandwidth interface to EAGLE via XBee is still available. This allows commanding emergency landings or monitoring the most important housekeeping data.

The OBC runs the real-time operating system *QNX* which executes the on-board software including the Guidance, Navigation, and Control algorithms. The main software system is built from a MATLAB/Simulink model. *Simulink Coder* generates "C" code from this model that is cross-compiled for the OBC. This enables a rapid prototyping functionality allowing quick software changes in between tests and directly using developed and tested Simulink algorithms without the necessity of porting the algorithm to the target platform.

4 Flight Envelope

The flight envelope of EAGLE defines restrictions and limits that are based on maximum ratings by a subsystem or are based on regulations and safety concerns. E. g. the maximal thrust is given by the selected type of the engine, that limits the acceleration. The maximal altitude EAGLE is allowed to fly is defined by the air traffic control authority and the corresponding flight permission granted for EAGLE.

The limits also depend on the environment where a test is conducted. Two main cases are defined within this document. First, the tethered flight environment which has very strict boundary conditions, except for the maturity of the software. The tethered flight environment is, of course, for testing algorithms which are not jet fully tested, but which can be tested within a safe environment (after extensive Software-in-the-Loop (SiL) testing)

Second, a free flight, that is envisioned for EAGLE within a restricted and reserved airspace.

4.1 NEST Environment for Suspended flight Tests

During initial operations and first tests with new algorithms, software and hardware configurations EAGLE should be operated in a safe environment. The NEST Environment for Suspended flight Tests (NEST) is a set-up from aluminum trusses shown in Figure 9 in which EAGLE can be constrained with different layouts of safety tethers. One main top tether is mandatory, extra tethers to hold EAGLE down and/or to the side are optional and should be used for early tests with respect to the maturity of the unit under test.

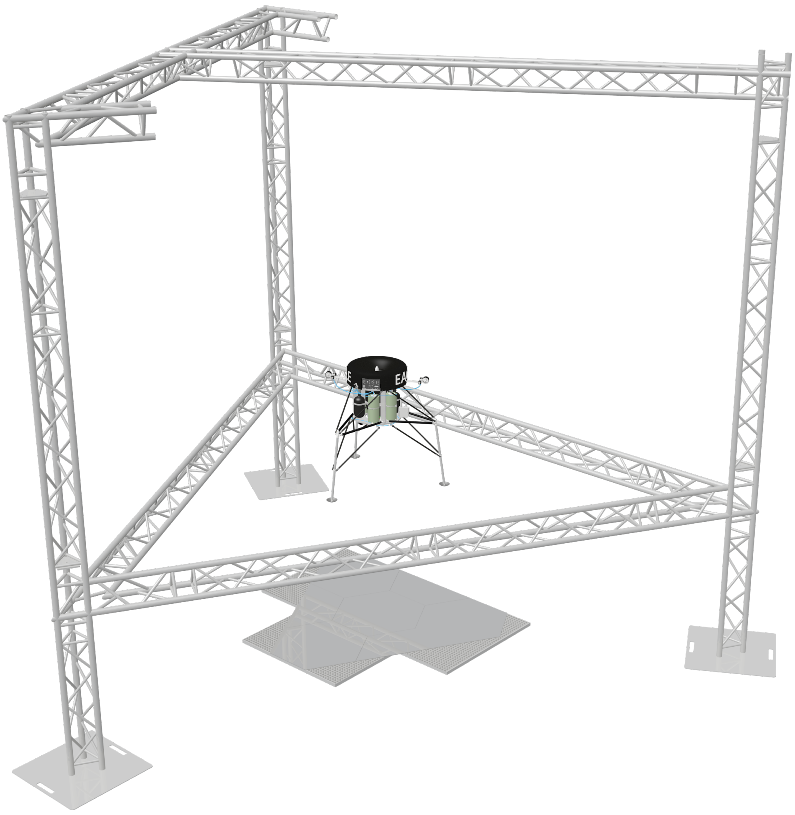


Figure 9: Tethered Flight Facility with EAGLE and Launch Pad

The triangular base length of the facility is 6 m. The height is 5.25 m.

The following Table 3 is given as a general guideline for planning tests within the tethered flight environment. For special tests some parameters can be adapted. The values provided in the table are for the nominal flight conditions. In case of an abort or some interactions with the tethers the limits for accelerations, rates, pitch/yaw angle, etc. can be violated.

Table 3: EAGLE Tethered Flight Envelope

Symbol	Unit	Value	Description
t_{Flight}	min	4	Flight time of EAGLE, based mainly on fuel

n_{max}	1	330 N/300 N	Thrust to weight ratio, with reduced maximal thrust
$t_{\text{Engine}_{\text{max}}}$	N	$n_{\text{max}} \cdot w_{EAGLE}$	Maximal engine thrust, reduced for safety reasons, relative to EAGLE's weight w_{EAGLE}
$\dot{m}_{\text{FuelFlow}_{\text{max}}}$	$\text{l}\,\text{s}^{-1}$	50	Maximal fuel flow into the engine under reduced maximal thrust
p_{max}	$^\circ\,\text{s}^{-1}$	30	Maximal roll rate
q_{max}	$^\circ\,\text{s}^{-1}$	15	Maximal pitch rate
r_{max}	$^\circ\,\text{s}^{-1}$	15	Maximal yaw rate
ϕ_{max}	°	± 15	Maximal roll angle, reduced by the FoV of ET-NAV
θ_{max}	°	± 15	Maximal pitch angle
ψ_{max}	°	± 15	Maximal yaw angle
h_{max}	m	2	Maximal height w.r.t. initial hanging point
v_{ascent}	$\text{m}\,\text{s}^{-1}$	0.5	Maximal vertical ascent velocity
v_{descent}	$\text{m}\,\text{s}^{-1}$	0.5	Maximal vertical descent velocity
$v_{\text{touch down}}$	$\text{m}\,\text{s}^{-1}$	0.5	Maximal touch down velocity
$v_{\text{horizontal}}$	$\text{m}\,\text{s}^{-1}$	1	Maximal horizontal velocity
$\delta_{TVC_{\text{max}}}$	°	12	Maximal absolute deflection angles of the TVC vanes
$\sigma_{\text{control}_\phi}$	°	<1	Roll controller steady state accuracy
Δp_{min}	s^{-1}	0.01	Minimum pulse of cold gas system (6 ms pulse $(t/I \cdot \Delta t)$)
$\sigma_{\text{GPS NAV}_r}$	m	2.5 / 0.05	Navigation system 1σ position accuracy in horizontal/vertical direction with GPS filter update
$\sigma_{\text{GPS NAV}_v}$	$\text{m}\,\text{s}^{-1}$	0.2 / 0.05	Navigation system 1σ velocity accuracy in horizontal/vertical direction with GPS filter update
$\sigma_{\text{ET-NAV NAV}_r}$	m	0.05 / 0.02	Navigation system 1σ position accuracy in horizontal/vertical direction with ET-NAV filter update
$\sigma_{\text{ET-NAV NAV}_v}$	$\text{m}\,\text{s}^{-1}$	0.1 / 0.05	Navigation system 1σ velocity accuracy in horizontal/vertical direction with ET-NAV filter update
$\sigma_{\text{NAV}_\theta}$	°	2/4	Navigation system 1σ attitude accuracy in pitch and yaw / heading direction with ET-NAV filter update
$\sigma_{\text{ET-NAV NAV}_\theta}$	°	1/1	Navigation system 1σ attitude accuracy in pitch and yaw / heading direction without ET-NAV filter update
$d_{\text{LA}_{\text{max}}}$	m	10	Maximal measuring distance of the laser altimeter
v_{wind}	$\text{m}\,\text{s}^{-1}$	10	Maximal allowed wind speed during flight

Table 4 lists the critical conditions that result in a test abort, manually or automated. In any case, the operator can abort a tests for other reasons than those given in the table if the operator anticipates a safety critical situation.

Table 4: Critical Tethered Flight Envelope

Symbol	Unit	Value	Description
θ_{max}	°	± 20	Maximal pitch angle
ψ_{max}	°	± 20	Maximal yaw angle
h_{max}	m	2.5	Maximal height w.r.t. initial hanging point
$p_{\text{horizontal}}$	m	1.5	Maximal lateral position w.r.t. initial hanging point
v_{ascent}	$\text{m}\,\text{s}^{-1}$	1	Maximal vertical ascent velocity
v_{descent}	$\text{m}\,\text{s}^{-1}$	1	Maximal vertical descent velocity
$v_{\text{horizontal}}$	$\text{m}\,\text{s}^{-1}$	1	Maximal horizontal velocity
v_{wind}	$\text{m}\,\text{s}^{-1}$	20	Maximal allowed wind speed during flight

4.2 Free Flight

Contrary to the flight envelope for the tethered flight, the limits given in Table 5 are to be followed at all times.

Table 5: EAGLE Free Flight Envelope

Symbol	Unit	Value	Description
t_{Flight}	min	4	Flight time of EAGLE, based mainly on fuel
n_{max}	1	400 N/300 N	Thrust to weight ratio
$t_{\mathrm{Engine}_{\mathrm{max}}}$	N	392	Maximal engine thrust
$\dot{m}_{\mathrm{FuelFlow}_{\mathrm{max}}}$	l s^{-1}	70	Maximal fuel flow into the engine
p_{max}	° s^{-1}	30	Maximal roll rate
q_{max}	° s^{-1}	20	Maximal pitch rate
r_{max}	° s^{-1}	20	Maximal yaw rate
ϕ_{max}	°	-	Maximal roll angle
θ_{max}	°	± 25	Maximal pitch angle
ψ_{max}	°	± 25	Maximal yaw angle
h_{max}	m	100	Maximal height above ground
v_{ascent}	m s^{-1}	5	Maximal vertical ascent velocity
	m s^{-1}	3	Maximal vertical descent velocity
v_{descent}	m s^{-1}	2	Maximal vertical descent velocity below 30 m height
	m s^{-1}	0.5	Maximal vertical descent velocity below 5 m height
$v_{\mathrm{touch\ down}}$	m s^{-1}	0.1	Maximal touch down velocity
$v_{\mathrm{horizontal}}$	m s^{-1}	10	Maximal horizontal velocity above 20 m height
	m s^{-1}	1	Maximal horizontal velocity below 20 m height
$\delta_{TVC_{\mathrm{max}}}$	°	12	Maximal absolute deflection angles of the TVC vanes
$\sigma_{\mathrm{control}_{\phi}}$	°	1	Roll controller steady state accuracy
Δp_{min}	s^{-1}	0.01	Minimum pulse of cold gas system (6 ms pulse)
$\sigma_{\mathrm{GPS\ NAV}_r}$	m	2.5 / 0.05	Navigation system 1σ position accuracy in horizontal/vertical direction with GPS filter update
$\sigma_{\mathrm{GPS\ NAV}_v}$	m s^{-1}	0.2 / 0.05	Navigation system 1σ velocity accuracy in horizontal/vertical direction with GPS filter update
$\sigma_{\mathrm{RTK\ NAV}_r}$	m	0.5 / 0.05	Navigation system 1σ position accuracy in horizontal/vertical direction with RTK filter update
$\sigma_{\mathrm{RTK\ NAV}_v}$	m s^{-1}	0.1 / 0.05	Navigation system 1σ velocity accuracy in horizontal/vertical direction with RTK filter update
$\sigma_{\mathrm{NAV}_{\theta}}$	°	2/4	Navigation system 1σ attitude accuracy in pitch and yaw / heading direction
$d_{\mathrm{LA}_{\mathrm{max}}}$	m	10	Maximal measuring distance of the laser altimeter
v_{wind}	m s^{-1}	4	Maximal allowed wind speed during flight

5 Performance

5.1 Turnaround Time

The Turnaround Time (TAT) is the duration between flight test with EAGLE. This time includes restocking of all consumables (battery power/cold-gas/fuel). Part of these task take their time, but they do not include manual labor, like recharging the battery (except for plugging in the umbilical connector). Recharging completely empty batteries requires one hour.

During the TAT additional task like saving housekeeping data and first data analysis is possible. This provides the opportunity to make decisions for the next flight, e. g., changing parameters and recompiling the code.

5.2 Payload Mass and Interface

For additional payload a mass budget of 1 kg is available. Furthermore, that the payload must be balanced w.r.t. the CoM. The mechanical interface will be defined according to the payloads need's and available options.

Unregulated power can be provided (7.4 V/10 A; 14.8 V/1 A; 22.2 V/1 A; 33.3 V/0.5 A). A fuse has to be foreseen as a safety measure. An alignment between payload and EAGLE frame can be provided only with an accuracy of approximately 5°.

5.3 Telemetry Bandwidth

The Wifi link allows for payload telemetry. A payload data rate of up to 10 KiB s^{-1} is possible.

The XBee link is only for safety critical commands and telemetry. Routing of payload data via XBee is not foreseen.

5.4 Control Range

The safe control distance between EAGLE and the Ground Station (GS) is defined by proper working of *both* wireless links (WiFi and XBee). From the characteristics of the carrier wave, the limiting link is WiFi. In open field communication is limited to 200 m.

5.5 Derived Limits

To understand part of the limits provided with the flight envelopes, this section will provide justifications.

5.5.1 Flight Time

The maximal flight time is limited by the consumables, i. e. fuel and cold-gas. For hovered flight a fuel flow of about 70 l h^{-1} is needed. With 6 L fuel we can assume a flight time of about 5 min. But including engine start, proper engine shutdown sequence, and safety margin, 4 min is the limit.

Depending on roll maneuvers the cold-gas can even further limit the flight time. Especially in the tethered flight facility a lot of cold-gas is used for holding the attitude under tether disturbances.

5.5.2 Maximal Velocities

The unknown aerodynamic forces and torques of EAGLE at high velocities may cause unstable flight states. They must be avoided. Free flight tests will show the actual limits.

5.6 Environment

5.6.1 Safety Distance

For test within the tethered flight facility the safety distance for the operations team is at least 15 m during operation. Single individuals can get the clearance to get closer under stricter regulations regarding Personal Protective Equipment (PPE). Other persons are not allowed to get closer.

The safety distance increases during free flights. Project personal is not allowed to get closer than 50 m to the flight path only during initial operation exceptions are allowed. A general safety distance of 300 m for observers is advised.

5.6.2 Noise Environment

Within a radius of 100 m noise protection equipment is mandatory during engine run time. Also, regarding equipment on-board of EAGLE a noise level of up to 120 dB(A) is to be expected.

5.6.3 Vibration Environment

EAGLE is a high frequency vibrations environment. The engine runs in the range of 20 000 RPM to 100 000 RPM (333.3 Hz to 1666.7 Hz). Higher frequencies can be reached through the interactions of the 7 inlet compressor blades, or the 23 turbine blades. The amplitude of the vibrations is small compared to helicopters.

5.7 Temperature Environment

The utilized battery technology on board of EAGLE is Lithium-ion Polymer (LiPo) based. Generally, they work at a room temperature of 20 °C. (To give a range were we expect well behavior: 0 °C to 35 °C.)

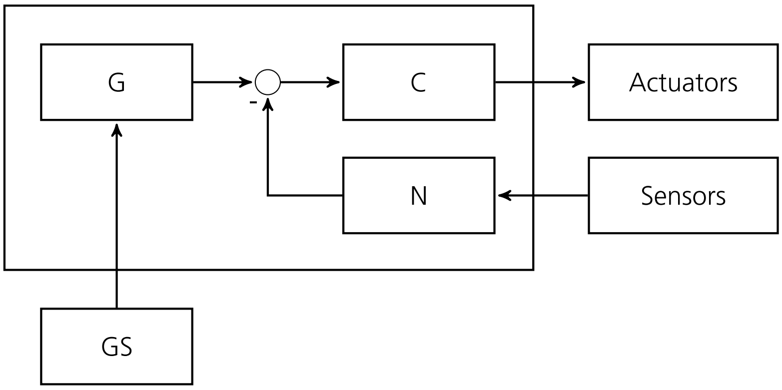


Figure 10: Base Guidance, Navigation, and Control System Overview

6 Guidance, Navigation, and Control

The on-board software of EAGLE always runs a basic set of algorithms for Guidance, Navigation, and Control (GNC). These algorithms are a robust set of tested algorithms that are active even if a new algorithm is being tested. The *base GNC* software is at least a back-up system but is also used in normal flight if the performance of a basic robust implementation suffices.

The simplified GNC set is depicted in Figure 10. The GS activates the (G)uidance, which, in a simple case, plays a trajectory, or in an even simpler case commands a set-point for the controllers. The deviation between the guidance and the (N)avigation is processed by the (C)ontroller that commands the actuators. In turn, the new measurements of the sensors are processed by the navigation system.

6.1 Guidance

The execution of maneuvers requires trajectories the controllers are able track. Two basic methods are available to command changes of the reference position and velocity. The simplest case is a single set-point that is directly fed to the controllers.

A more advanced algorithm is available for executing maneuvers. The *polynomial guidance* method computes online a continuous trajectory between current position and final position, and it derivatives, i. e. velocity and acceleration. Bounds are imposed on the derivatives to remain within the allowed envelope from Section 4 during the maneuver.

6.2 Navigation

The navigation system of EAGLE estimates the current state of the lander with respect to position, velocity, and attitude. The whole system consists of multiple sensors and software algorithms which run on the OBC.

Figure 11 shows the block diagram of the navigation system which processes the sensors, conducting strapdown integration of the inertial sensors. Further sensor measurements are then fused within a Kalman filter (KF) for estimating the current state of EAGLE. With the estimated error states of the Inertial Measurement Unit (IMU) the angular rates and linear accelerations are corrected and transformed. Together with the system state, the corrected measurements are relayed to the guidance and control subsystems.

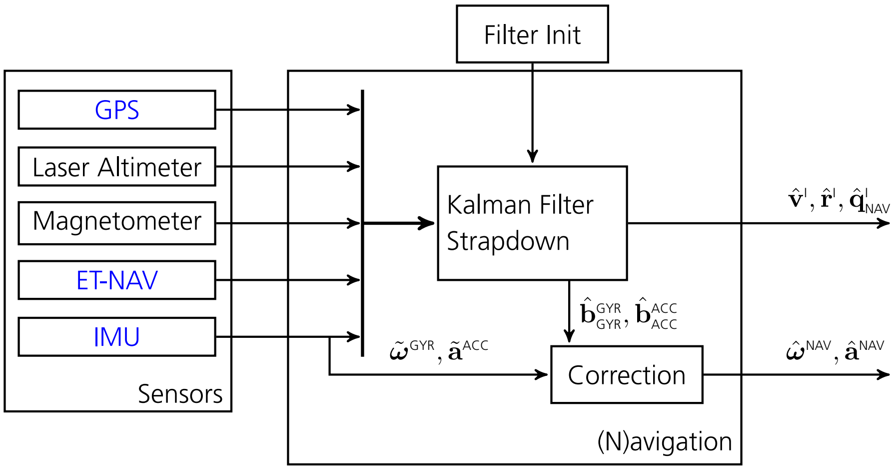


Figure 11: Base Navigation System

The main idea of a KF design is to use different sensors and combine their strength into one navigation solution which is available with a high frequency. The available sensors are the following:

GPS Small GPS receiver for Navstar L1 frequency
RTK GPS raw measurement augmentation with a second stationary receiver at the GS for high precision positioning
IMU Microelectromechanical Systems (MEMS) based IMU
Laser altimeter High rate laser altimeter with limited range of about 10 m.
Magnetometer Low accuracy magnetometer
ET-NAV The EAGLE Tag Navigator is an optical sensor that is based on *April Tag* that uses 2D pattern to navigate. Within close distance to such tags the navigation accuracy is a couple of centimeters and around one degree for attitude. Especially, within the Tethered Flight Facility it is necessary to guarantee a good navigation solution for precision flight.

The user can expect the navigation solution with the IMU sample frequency, which is at least 100 Hz. The navigation solution can be calculated w.r.t. any typical reference frame (ECEF, NED or B, M etc.)

6.3 Control

The control subsystem, shown in Figure 12, bundles the different controllers implemented on EAGLE. The attitude of EAGLE is controlled via a roll control system that employs cold gas nozzles and a Thrust Vector Control (TVC) system that deflects the engine exhaust to generate a torque around the pitch and yaw axes. The altitude is controlled with the jet engine's ECU.

Roll Control

For controlling the roll axis of EAGLE a roll control system was implemented that utilizes compressed air that is released through nozzles. These nozzles are mounted on a lever arm (cf. Figure 7) that transforms the thrust into a control moment. The valves are on/off valves which require a pulse scheme to control the attitude. Figure 13 depicts the opening of the valves over a short period of time. The base control period $t_{\Delta_{\mathrm{PWM}}}$ is 40 ms, the actual time the valve is open is given by the pulse width $t_{\delta_{\mathrm{PWM}}}$. The pulse width can be commanded different durations to generate a variable thrust level (averaged over time) for a more precise attitude control.

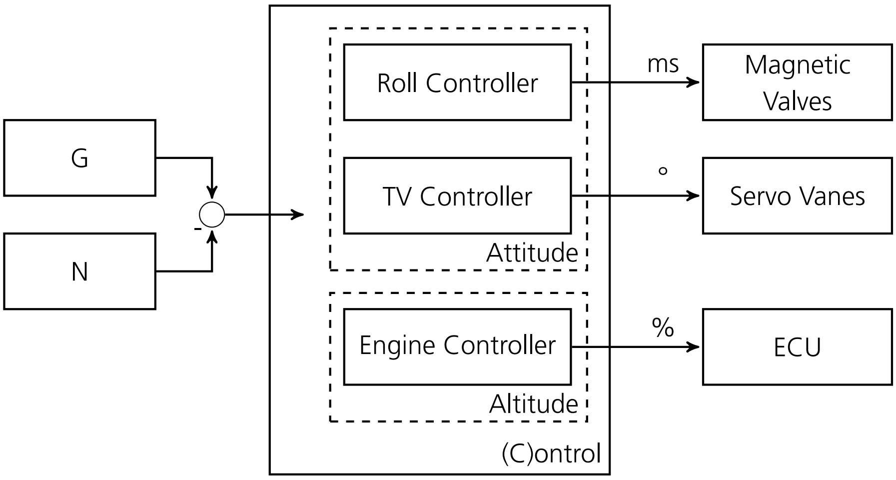


Figure 12: Base Control System

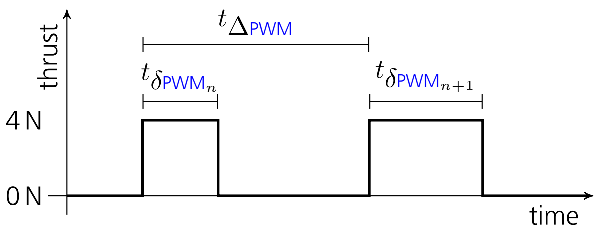


Figure 13: Cold Gas Valve PWM with Period $t_{\Delta_{\text{PWM}}}$ and Pulse Width $t_{\delta_{\text{PWM}}}$

Thrust Vector Control and Engine Control

For achieving high quality attitude and altitude control results proper actuator identification was conducted.

The jet engine's thrust was statically identified and is shown in Figure 14a, the dynamic behavior can be approximated as a second order delay. It is commanded with a frequency of 16 Hz.

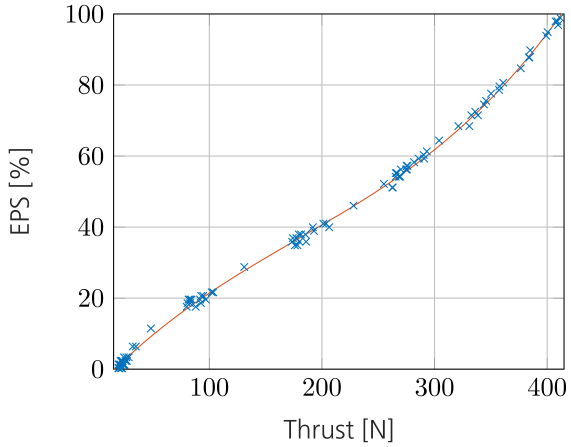
The identification of the vanes is given in Figure 14b. The vane's servo motors are commanded via PWM. The diagrams show the command around a set point, which is where the vanes are trimmed. Roughly, we can convert "ms" to "°" with a factor of 100, meaning the diagram shows the vane deflections from −10° to 10° over a thrust range of 240 N to 300 N.

The dynamic behavior can be modeled with a first or second order delay. The time constants are small (the actuator and the air stream are very fast), compared to the overall system. The control frequency can be varied. A frequency of 25 Hz is reasonable, higher frequencies are possible.

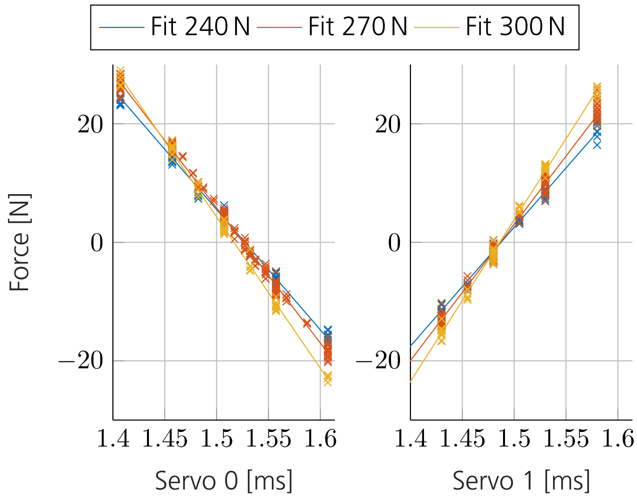
To generate the attitude control torques the lever arm of the thrust vector vanes with respect to the body frame must be known. It is about 0.2 m, but it varies with the fuel mass.

7 Data Monitoring, Interaction, and Recording

EAGLE is monitored in real time by a ground station computer. Before lift-off, the on-board software can be monitored and checked for consistency. Sensor values can be manually checked, the output of the navigation filter must appear



(a) Engine Thrust Identification



(b) Thrust Depended Vane Efficiency

Figure 14: Identification of the TVC System

stable and logical, and the actuators can be stimulated to make sure everything is working as planned.

The Electronic Ground Support Equipment (EGSE) includes all hardware and software that is necessary for running the ground station software and also software that assists in post-processing logging data. This software framework was designed for the whole process from conduction a test, by monitoring and controlling, and post-processing the synchronized data of all sensors, filters, commands, etc.

7.1 Ground Control

The main part of the EGSE is a computer that runs the *Ground Control* program. It is a Graphical User Interface (GUI) with a backend to control the Telemetry/Telecommand (TM/TC) flow. The GUI is highly versatile with different tabs for different purposes of monitoring EAGLE. The main tab is called the *Pilot Display* as depicted in Figure 15. It is build up from typical aeronautic instrument representations, that are used to monitor the general status. The main instrument is the Primary Flight Display (PFD) that indicates the navigation solution for the attitude, velocity, and height, second to that is a map widget showing the position navigation solution on a moving map. The row of round instruments are indicators for single raw measurements, like the Exhaust Gas Temperature (EGT) of the jet engine, true heading (compass), or laser altimeter distance.

The rows of colored blocks are status indicators of EAGLE's subsystems or individual sensors that show the general status according to the following scheme.

Table 6: General Status Representation

Value	Color	Description
0	Green	Nominal
1	Yellow	Warning
2	Blinking Yellow/Red	Critical
3	Red	Error

To the right of the instruments is a list of all current values of variables defined in the Interface Control Document (ICD), (see Section 9.1). Additionally, the receive time, their value range, and, by setting the background color of the rows,

Figure 15: Ground Control GUI: Pilot View

the status of each individual value is indicated. The color coding is equivalent to the status indicators, except that "Nominal" is left in white. Below the variable list an event view shows the most recent events, like decoding errors, dis-/connection events with EAGLE, etc.

Figure 16 shows another tab that can plot all values that are defined in the ICD. Especially during initial operation or specific tests, this view is very useful.

Other tabs can be programmed to enhance the monitoring process, or for special test an additional layout of values and parameters can be implemented.

Sending parameters to EAGLE is possible in the *Telecommands* and *Engine Control* tab for, e. g. changing the reference pressure for the barometer, or starting the jet engine.

7.2 Post-Processing

Both the *Ground Control* program, and the server program running on EAGLE generate a binary logging file which is easily converted into a MATLAB mat-file. The on-board file provides logging information at higher sampling frequencies. But in case the on-board file is not available low rate data from the ground station logging can be used. The time stamping of the *Ground Control* is based on the system time of the EGSE PC and the actual arrival time of a packet. So a direct comparison between both files is not possible. Additional MATLAB functions clean up the time series for a simple inspection.

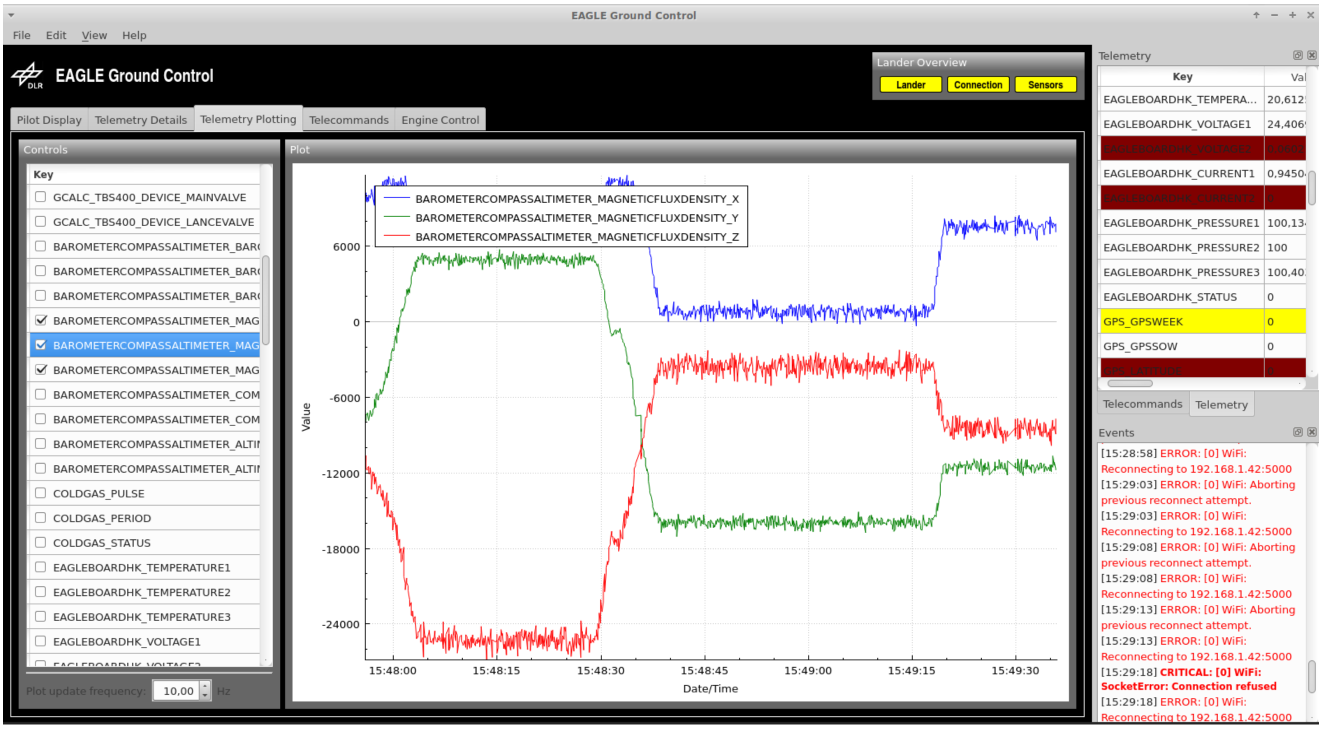


Figure 16: Ground Control GUI: Live Plot View

7.3 Telemetry/Telecommand Software Interface

The interface between the on-board software and ground station software is based on the definition of user data to be sent back and forth. The major flow of information is assumed to be telemetry to the ground station. Telecommands are just simple parameters with an attached variable. The parameter list can be easily extended with a given name and storage type. Setting a parameter is logged by the EGSE and the lander.

Telemetry packets generally include groups of variables that belong together, like the navigation solution which includes position, velocity, and attitude information. For all variables three ranges are defined against which the value is successively checked (*Nominal*, *Warning*, *Error*). If the value falls into a range it is labeled as such. If it falls into none, it is labeled *Critical*. Section 7.1 explains where this information can be utilized.

The packets are built from Comma Separated Values (CSV) files, as an example the altimeter packet definition is:

```
1  packet description: The measurements of the altimeter packet.
2  call function when packet is received: NONE
3  #name type    unit  min_nom max_nom min_warn  max_warn  min_err max_err description
4  Distance  f32_t \meter  .5  10. .3  12. .1  20. altimeterDistance The laser altimeter distance (meter)
       value.
5  Feet2Ground f32_t \meter  .5  10. .3  12. .1  20. Estimation of the distance between EAGLEs feet and
       the ground floor, if leveled. It fits a linear function into the last X measurements and estimates
       the current value.
6  Feet2Ground_bias  f32_t \meter  −1. 0.  1.1 .1  −1.3  .3  The bias for the altimeter measurement
       gaining the feet2ground. CAUTION Feet2Ground does a fit, so the difference between distance and
       feet2ground is not necessarily exactly the bias.
7  Status  uint8_t  0 0 1 1 3 3 Status 0:Nominal, 1:Warning, 3:Error
```

As the separator the tabulator ("\t") was chosen. The syntax and sequence of this example must be exactly complied with. It is to be noticed, that vector-valued variables are not possible and a naming scheme must be applied, cf. position definition of the GPS packet in Table 11. Line 2 is used in case a special function is to be run inside the Ground Control framework if the current packet was received.

The definitions of all packets are parsed by a set of MATLAB functions. The process then automatically builds all the necessary extensions to the EGSE software, like decoding and encoding functions, and for the lander the Simulink blocks are generated. As an example the altimeter packet can be seen in Figure 17.

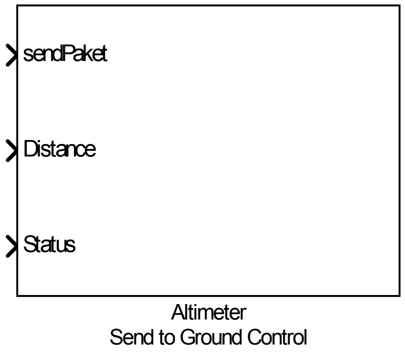


Figure 17: Altimeter Packet Interface in Simulink

After the definition, parsing, and recompilation of all software, also the conversion program from log-file to MATLAB mat-file includes the new or modified packets. This shows the restriction that it is not possible to add a packet definition during run-time of either the EGSE or the on-board software. But the automated process makes it a matter of minutes to change or extend the interface.

Parameters for commanding the lander are defined in a similar way, but they are not bundled within a packet. Each single parameter can be send at a time, or multiple parameters at the same time. A parameter does not have limits, only *name*, *type*, *unit*, and *description*:

```
#name type  unit  default description
qnh f32_t \pascal 101325.0  The pressure at sea level recalculated from the current altitude with the
     parameters of the ISA
amt_pwrSetting  f32_t \per100 0 AMT Titan engine power setting (percent), normalized for pump voltage
```

8 User Modification

One of EAGLE's main design goals is to build a test environment which can be adapted in a very flexible way. This flexibility is given for most parts of the use cases of a landing demonstrator. It can be utilized to test new navigation algorithms or sensors, small payloads, sloshing test etc. Under high safety restriction it can be seen also as a platform for *trial-and-error* testing, because the TAT, i. e. refueling, recharging, software modifications, etc., is kept very short.

To ensure the safe operation of EAGLE (and personnel and observers) some guidelines must be abided by and of course some restrictions for modifications are given.

For EAGLE a high flexibility for experiments is foreseen. Since every experiment has to match the system capabilities and has to follow safety procedures, the setup is very complex. For that reason this section provides boundary conditions.

8.1 Hardware

Integrating a payload on EAGLE is possible. Due to the added mass and the changed CoM the possibilities are limited. Accepting a limited flight envelope a payload mass of up to 1 kg is possible. Furthermore, EAGLE must be re-balanced, which increases the mass even more. Interfaces to EAGLE's power and/or data system must be clarified, implemented, and tested in advance to reduce risks of affecting safe operation.

8.2 Software

EAGLE as a testbed for new software implementation of algorithm is intended by design. To ensure safe operations, a basic set of GNC implementations will run at all time, taking back the control of EAGLE if specified limits were violated. This infrastructure for switching between the basic flight control system and an experimental flight control system allows also to switch on (parts of) the experimental system during flight, not only as a backup in case of emergency.

User provided software will be tested by SiL and Hardware-in-the-Loop (HiL) tests as well as with checks in a lab environment. E. g. a new TVC can be tested by tilting EAGLE and looking at the controlled vanes. This can already show basic interface problems (coordinate frame, actuator commands). Software which is not real-time safe or possesses the possibility of taking too much processing time is always run in an additional, partly sand-boxed, thread to reduce the risk of affecting the base GNC.

Additional sensor inputs to the navigation filter are implemented with safety features to ignore measurements if necessary. If the filter structure is changed more than an additional filter update function that can be simply switched off, the original filter will also run in parallel with the capability to overrule the modified version.

8.3 Verification

The verification process of new software includes proving proper functioning within SiL and HiL environments. All simulation environments and also the environment for the on-board software provide the identical interface for GNC algorithms within Simulink. This has the advantage that it is possible to go through the verification chain fast and efficiently.

Parameters have to be defined that automatically switch to the backup GNC systems if limits are violated. E. g. limits for the guidance are:

- Maximal commanded velocity
- An area where it is safe to fly and for which the flight permission is granted
- Maximal commanded pitch and yaw angles

Limits for navigation:

- Navigation state is not allowed to differ from the backup navigation by a given amount

Limits for control:

- Actuator limits
- Control deviation

Depending on the limit which has been violated, either one backup system is activated or the whole backup GNC is activated with a guidance back towards the launch site or an immediate emergency landing procedure is initiated.

9 System Parameters

Configuration branch used for the following section: »branches/EAGLE_MK1«

Mass, Center of Mass, Inertia

Table 7: Mass, Center of Mass, and Inertia of EAGLE

Symbol	Type	Unit	Value	Description
$m_{\text{RiggingAdapter}}$	double	kg	2.33×10^{-1}	Mass of the pyramid rigging adapter
m_{dry}	double	kg	2.56×10^{1}	Dry mass of EAGLE
$\mathbf{l}_{\text{B}}^{\text{M}}$	double	m	$\begin{bmatrix} 1.92 \times 10^{-1} & 0.00 & 0.00 \end{bmatrix}$	Position of CoM (Origin of body frame) in mechanical frame without fuel.
I_{B}^{B}	double	kg m^2	$\begin{bmatrix} 2.00 & 0.00 & 0.00 \\ 0.00 & 1.70 & 0.00 \\ 0.00 & 0.00 & 1.70 \end{bmatrix}$	Inertia w.r.t body frame

Alignment

Table 8: Parameters for the alignment of the used system

Symbol	Type	Unit	Value	Description
$\mathbf{l}_{\text{NAV}}^{\text{M}}$	double	m	$\begin{bmatrix} 3.90 \times 10^{-1} \\ 6.97 \times 10^{-2} \\ -1.73 \times 10^{-1} \end{bmatrix}$	Lever arm of NAV fram in M coordinates
$\mathbf{l}_{\text{BARO}}^{\text{NAV}}$	double	m	$\begin{bmatrix} -7.07 \times 10^{-2} \\ -2.92 \times 10^{-1} \\ -5.12 \times 10^{-4} \end{bmatrix}$	Lever arm of barometer in NAV coordinates
$\mathbf{l}_{\text{GPS}}^{\text{NAV}}$	double	m	$\begin{bmatrix} 3.97 \times 10^{-3} \\ -2.33 \times 10^{-1} \\ -1.27 \times 10^{-1} \end{bmatrix}$	Lever arm of GPS antenna in NAV coordinates
$\mathbf{l}_{\text{MAG}}^{\text{NAV}}$	double	m	$\begin{bmatrix} -7.08 \times 10^{-2} \\ -3.13 \times 10^{-1} \\ -5.46 \times 10^{-4} \end{bmatrix}$	Lever arm of magnetometer in NAV coordinates
$\mathbf{l}_{\text{LA}}^{\text{NAV}}$	double	m	$\begin{bmatrix} -3.40 \times 10^{-1} \\ -2.37 \times 10^{-1} \\ 3.74 \times 10^{-1} \end{bmatrix}$	Lever arm of laser altimeter in NAV coordinates
$\mathbf{l}_{\text{ETNAV}}^{\text{NAV}}$	double	m	$\begin{bmatrix} -2.38 \times 10^{-1} \\ -3.29 \times 10^{-1} \\ 3.10 \times 10^{-3} \end{bmatrix}$	Lever arm of ET-NAV camera in NAV coordinates
$\mathbf{l}_{\text{TVC}}^{\text{NAV}}$	double	m	$\begin{bmatrix} -1.75 \times 10^{-1} \\ -7.35 \times 10^{-2} \\ 4.07 \times 10^{-1} \end{bmatrix}$	Lever arm of TVC frame in NAV coordinates
$\mathbf{l}_{\text{ACC}}^{\text{NAV}}$	double	m	$\begin{bmatrix} 0.00 & 0.00 & 0.00 \end{bmatrix}$	Lever arm(s) of accelerometers in NAV coordinates
$\mathbf{u}_{\text{LA}}^{\text{NAV}}$	double		$\begin{bmatrix} -7.93 \times 10^{-3} \\ -1.58 \times 10^{-3} \\ 1.00 \end{bmatrix}$	Laser orientation in NAV coordinates
$T_{\text{ACC}}^{\text{NAV}}$	double		$\begin{bmatrix} 1.00 & 0.00 & 0.00 \\ 0.00 & 1.00 & 0.00 \\ 0.00 & 0.00 & 1.00 \end{bmatrix}$	Transformation from ACC frame to NAV frame
$T_{\text{GYR}}^{\text{NAV}}$	double		$\begin{bmatrix} 1.00 & 0.00 & 0.00 \\ 0.00 & 1.00 & 0.00 \\ 0.00 & 0.00 & 1.00 \end{bmatrix}$	Transformation from GYR frame to NAV frame

$T_{\mathrm{M}}^{\mathrm{NAV}}$	double		$\begin{bmatrix} 7.93\times10^{-3} & 7.05\times10^{-1} & -7.09\times10^{-1} \\ 1.58\times10^{-3} & -7.09\times10^{-1} & -7.05\times10^{-1} \\ -1.00 & 4.47\times10^{-3} & -6.74\times10^{-3} \end{bmatrix}$	Transformation from M frame to NAV frame
$T_{\mathrm{NAV}}^{\mathrm{MAG}}$	double		$\begin{bmatrix} -9.07\times10^{-1} & -4.20\times10^{-1} & -7.86\times10^{-3} \\ -4.20\times10^{-1} & 9.07\times10^{-1} & -1.89\times10^{-3} \\ 7.93\times10^{-3} & 1.58\times10^{-3} & -1.00 \end{bmatrix}$	Transformation from NAV frame to MAG frame
$T_{\mathrm{NAV}}^{\mathrm{ETNAV}}$	double		$\begin{bmatrix} 9.72\times10^{-1} & -2.36\times10^{-1} & 7.33\times10^{-3} \\ -8.83\times10^{-2} & -3.34\times10^{-1} & 9.38\times10^{-1} \\ -2.19\times10^{-1} & -9.13\times10^{-1} & -3.45\times10^{-1} \end{bmatrix}$	Transformation from NAV frame to ETNAV frame
$T_{\mathrm{NAV}}^{\mathrm{TVC}}$	double		$\begin{bmatrix} 2.57\times10^{-3} & 1.00 & 1.60\times10^{-3} \\ 1.00 & -2.59\times10^{-3} & 7.92\times10^{-3} \\ 7.93\times10^{-3} & 1.58\times10^{-3} & -1.00 \end{bmatrix}$	Transformation from NAV frame to TVC frame
$T_{\mathrm{M}}^{\mathrm{TVC}}$	double		$\begin{bmatrix} -5.41\times10^{-10} & -7.07\times10^{-1} & -7.07\times10^{-1} \\ -2.67\times10^{-9} & 7.07\times10^{-1} & -7.07\times10^{-1} \\ 1.00 & -1.51\times10^{-9} & 2.27\times10^{-9} \end{bmatrix}$	Transformation M to TVC
$l_{\mathrm{FrontFeet}}^{\mathrm{M}}$	double	m	$\begin{bmatrix} -6.20\times10^{-1} & 0.00 & 6.36\times10^{-1} \end{bmatrix}$	Front feet position in mech coordinates
$l_{\mathrm{RearLeftFeet}}^{\mathrm{M}}$	double	m	$\begin{bmatrix} -6.20\times10^{-1} & -5.51\times10^{-1} & -3.18\times10^{-1} \end{bmatrix}$	Rear left feet position in mech coordinates
$l_{\mathrm{RearRightFeet}}^{\mathrm{M}}$	double	m	$\begin{bmatrix} -6.20\times10^{-1} & 5.51\times10^{-1} & -3.18\times10^{-1} \end{bmatrix}$	Rear right feet position in mech coordinates
$l_{\mathrm{FrontLegTip}}^{\mathrm{M}}$	double	m	$\begin{bmatrix} 1.42\times10^{-2} & 0.00 & 5.42\times10^{-1} \end{bmatrix}$	Front Leg tip (connector for tether)
$l_{\mathrm{RearLeftLegTip}}^{\mathrm{M}}$	double	m	$\begin{bmatrix} 1.42\times10^{-2} & -4.69\times10^{-1} & -2.71\times10^{-1} \end{bmatrix}$	Rear left Leg tip (connector for tether)
$l_{\mathrm{RearRichtLegTip}}^{\mathrm{M}}$	double	m	$\begin{bmatrix} 1.42\times10^{-2} & 4.69\times10^{-1} & -2.71\times10^{-1} \end{bmatrix}$	Rear right Leg tip (connector for tether)
$l_{\mathrm{InletRingFront}}^{\mathrm{M}}$	double	m	$\begin{bmatrix} 5.13\times10^{-1} & 0.00 & 2.75\times10^{-1} \end{bmatrix}$	Front Inlet ring point (for simulation)
$l_{\mathrm{InletRingRearLeft}}^{\mathrm{M}}$	double	m	$\begin{bmatrix} 5.13\times10^{-1} & -2.38\times10^{-1} & -1.38\times10^{-1} \end{bmatrix}$	Rear left Inlet ring point (for simulation)
$l_{\mathrm{InletRingRearRight}}^{\mathrm{M}}$	double	m	$\begin{bmatrix} 5.13\times10^{-1} & 2.38\times10^{-1} & -1.38\times10^{-1} \end{bmatrix}$	Rear right Inlet ring point (for simulation)

9.1 Example On-board to Ground Interfaces

Table 9: The important measurement data from the AMT Titan jet engine

Name	Type	Unit	Nominal		Warning		Error		Description
			min	max	min	max	min	max	
engineStatus	uint8_t		8	127	0	224	0	255	AMT Titan Engine Status 8:Start Clearance, 16:Starting, 32: Started up, 64: Idle Calibration, 96: Full op. running, 224: Max. RPM reached
switchPos	uint8_t		2	4	1	5	0	5	AMT Titan Operator Switch status, 1: Emergency stop, 2: Auto stop, 4: Running
errors	uint8_t		0	0	0	0	0	255	AMT Titan error flags, 0: OK >0: Errors
throttleRX	f32_t	/100	0.	100.	0.	110.	0.	200.	AMT Titan received throttle setting (internal)
vout	f32_t	V	1.0	4.2	0.9	5.0	0	10.	AMT Titan fuel pump voltage
enginespeed	f32_t	RPM	25000.	94000.	0.	110000.	0.	500000.	AMT Titan measured engine speed

EGT	f32_t	°C	500.	850.	0.	1200.	-40.	5000.	AMT Titan exhaust gas temperature
curPwrSetting	f32_t	/100	0.	100.	-5.	110.	-10.	200.	AMT Titan current engine power setting (calculated from vout)
status	uint8_t		0	0	1	1	3	3	AMT Titan Status 0:Nominal, 1:Warning, 3:Error

Table 10: The measurements of the altimeter packet.

Name	Type	Unit	Nominal		Warning		Error		Description
			min	max	min	max	min	max	
Distance	f32_t	m	.5	10.	.3	12.	.1	20.	altimeterDistance The laser altimeter distance (meter) value.
Feet2Ground	f32_t	m	.5	10.	.3	12.	.1	20.	Estimation of the distance between EAGLEs feet and the ground floor, if leveled. It fits a linear function into the last X measurements and estimates the current value.
Feet2Ground_bias	f32_t	m	-1.	0.	1.1	.1	-1.3	.3	The bias for the altimeter measurement gaining the feet2ground. CAUTION Feet2Ground does a fit, so the difference between distance and feet2ground is not necessarily exactly the bias.
Status	uint8_t		0	0	1	1	3	3	Status 0:Nominal, 1:Warning, 3:Error

Table 11: The GPS Ublox Neo-M8P solution packet.

Name	Type	Unit	Nominal		Warning		Error		Description
			min	max	min	max	min	max	
Date_Year	uint16_t		2014	2025	0	0	0	0	GPS Timestamp Year
Date_Month	uint8_t		1	12	0	0	0	0	GPS timestamp Month
Date_Day	uint8_t		1	30	0	0	0	0	GPS Timestamp Day
Time_Hour	uint8_t		0	23	0	0	0	0	GPS Timestamp Hour
Time_Minute	uint8_t		0	59	0	0	0	0	GPS Timestamp Minute
Time_Second	uint8_t		0	59	0	0	0	0	GPS Timestamp Second
Time_mSecond	uint16_t		0	999	0	0	0	0	GPS Timestamp milli Second
GPSWeek	int16_t	Week	0	2000	-1	1	-2	2	GPS week
GPSToW	f64_t	s	0.	630000.	-1.	1.	-2.	2.	GPS Time of Week in fractional seconds
r_ECEF_x	f64_t	m	0.	0.	0.	0.	0.	0.	The x-component of the GPS position vector
r_ECEF_y	f64_t	m	0.	0.	0.	0.	0.	0.	The y-component of the GPS position vector
r_ECEF_z	f64_t	m	0.	0.	0.	0.	0.	0.	The z-component of the GPS position vector
PositionAccuracy	f32_t	m	0.	0.	0.	0.	0.	0.	The position accuracy of the GPS position vector
v_ECEF_x	f64_t	$m\,s^{-1}$	-.5	.5	-1.	1.	-2.	2.	The x-component of the GPS velocity vector
v_ECEF_y	f64_t	$m\,s^{-1}$	-.5	.5	-1.	1.	-2.	2.	The y-component of the GPS velocity vector
v_ECEF_z	f64_t	$m\,s^{-1}$	-.5	.5	-1.	1.	-2.	2.	The z-component of the GPS velocity vector

VelocityAccuracy	f32_t	$m\,s^{-1}$	0.	0.	0.	0.	0.	0.	The velocity accuracy of the GPS velocity vector
ValidSatellites	uint8_t		0	0	0	0	0	0	Number of Satellites used to generate solution
SolutionStatus	uint8_t		1	1	2	2	0	0	0: No carrier phase range solution 1: Float solution 2: Fix Solution
status	uint8_t		0	0	1	1	3	3	IMU Status 0:Nominal, 1:Warning, 3:Error

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